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PROCESS-BASED MODEL OF GRAIN LIFTING FROM RIVER BED TO ESTIMATE SUSPENDED-SEDIMENT CONCENTRATION IN A SMALL HEADWATER BASIN

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ABSTRACT

Suspended sediment is supplied from river bed sediment in Hiyamizusawa Brook, Hokkaido, Japan, during the early snowmelt season. The stirring up of fine grains from the river bed is an important control of the time variation of suspended-sediment flux. In this stream, about 10 per cent of the river bed is covered with sand sediment, 80 per cent with cobbles and/or pebbles and the remaining 10 per cent is exposed bedrock. A model previously used to explain the stirring up of fine grains within a cobble and pebble bed is applied to a sand bed, with the modification that fine grains in a sand bed are assumed to be stirred up from the tractive layer formed on the surface, whereas those in a cobble and pebble bed are assumed to be stirred up from the gaps formed by the selective movement of pebbles on the river bed. The lift force acting at the river bed is estimated from the bed shear stress, and the maximum grain size capable of being stirred up was calculated from the lift force. Consequently, the amount of fine material stirred up from the river bed is estimated from the grain size distribution of river bed sediment, and the suspended-sediment flux is thus calculated. All stirred-up fines are assumed to become suspended sediment. The simulated time variation of suspended-sediment concentration was similar to that obtained in the field study. The calculated grain size of suspended sediment was also equivalent to the field data.

KEY WORDS suspended-sediment concentration; time variation; grain lift process; grain size; tractive force

INTRODUCTION

It is well known that several types of hysteresis exist between river discharge and suspended-sediment concentration (SSC) or suspended-sediment flux (SSF) (e.g. Allen, 1974; Takayama, 1974; Walling and Webb, 1987; Park, 1991, 1992; Kurashige, 1994a). In many cases the peak of SSC or SSF occurs before or almost concurrent with the peak discharge in small basins. In some cases it occurs after the peak discharge (Kurashige, 1994a). Williams (1989) proposed a general classification of hysteresis types, and pointed out that the occurrence of each type was affected both by runoff process and sediment supply process in a basin. Kurashige (1994a) explained qualitatively the occurrence of some hysteresis types in forms of actual processes of suspended-sediment supply in small basins.

Nevertheless, the SSC or SSF has rarely been predicted from the actual process of suspended-sediment supply in a basin. In many studies, they were predicted from an empirical relationship between SSC (C) and river discharge (Q), i.e.

$$C = aQ^b \tag{1}$$

where a and b are empirical constants, but SSC and SSF commonly produce poor correlations with discharge (e.g. Walling, 1977; Olive *et al.*, 1980; Walling and Webb, 1981; Ferguson, 1986; Sutherland and Bryan, 1990). Accordingly, the prediction of SSC or SSF using Equation (1) usually produces substantial errors in the resulting estimates (e.g. Olive *et al.*, 1980; Walling and Webb, 1981; Dickinson, 1981; Farr

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and Clarke, 1984; Ferguson, 1986; Al-Ansari *et al.*, 1988). These errors are caused not only by the logarithmic form of the correlation but also by the existence of other factors which can increase the hysteresis. Other researchers have considered using numerical models to improve the low accuracy of the simple estimation by Equation (1). For example, the input–output model proposed by Sharma *et al.* (1979), the digital filter model proposed by Zhang *et al.* (1989), and the transfer–function/noise model proposed by Lemke (1990) have obtained good results. However, these methods have not been based on the actual process of suspended-sediment supply to rivers.

On the other hand, some researchers have tried to explain the time variation of SSC from the process of suspended-sediment supply to rivers. Walling and Webb (1982) introduced the concept of sediment availability to interpret the time variation of SSC. They considered, for example, that the peak of SSC may occur earlier than the peak of discharge if the available sediment is restricted to the lower portion of the basin or if the available sediment is exhausted as the storm event proceeds. VanSickle and Beschta (1983) combined a washout function with Equation (1) to explain the exhaustion of suspended sediment during a storm event, and simulated the time variation of SSC in which its peak occurred before that of discharge. These studies have provided the first steps towards an understanding of hysteresis, but the actual process of suspended-sediment supply remains unclear.

Meanwhile, the time variation of SSC can be simulated based on the actual process of suspended-sediment supply only when the process is clearly understood. Kurashige (1985a) obtained the hysteresis that the peak of SSC appeared earlier than the peak of discharge in the early snowmelt season in Bankei Brook, Hokkaido, Japan. The grain-size distribution of suspended sediment was compared with the grain-size distributions of river-bed sediment, river-bank sediment, hillslope regolith, etc. in the basin. Further, with observation of the suspended-sediment supply, it was concluded that the suspended sediment was stirred up from the river-bed sediment in this case. Fine grains in the river-bed sediment were stirred up into the river water through the gaps between the gravel which covered the river-bed surface. Kurashige (1985b) considered the physical process whereby this occurred, and the time variation of SSC was simulated by his original 'grain lift model', which explained not only the time variation of SSC but also the grain-size distribution of suspended sediment. The outline of the grain lift model is described later in this paper.

In Hiyamizusawa Brook, Hokkaido, Japan, where about 10 per cent of the river bed is covered with sandy materials (Kurashige, 1993a), Kurashige (1993b) obtained a case in which the peak of SSC appeared earlier than the peak of discharge in the early snowmelt season. From the grain-size distribution of suspended sediment, he judged that most suspended sediment was supplied from the sand bed sediment. In this study, the time variation of SSC obtained in Hiyamizusawa Brook is simulated by applying the grain lift model to sand river-bed sediment.

FIELD STUDY

The Hiyamizusawa Brook basin, with an area of 0·93 km^2 (Figure 1), is located in a mountainous region near Sapporo, Japan. The basin has two major flood seasons in a year: the snowmelt season from early April to mid-May, and the summer rainy reason from mid-August to mid-October. The period from late October to late March is the snowy season, and snow covers the basin from December to April to a depth of several metres. The hillslope is covered by a mixed forest of fir, maple and birch. The geology of the basin is composed of quartz porphyry and andesitic agglomerate. In the summer of 1989 a new unpaved road was constructed in this basin.

Kurashige (1993a) classified the river bed of Hiyamizusawa Brook into four types: cobble bed, pebble bed, sand bed and exposed bedrock bed. The cobble bed consists of cobbles (20–30 cm in diameter), and the space between cobbles is filled with pebbles, small granules and coarse sand. The pebble bed is composed of pebbles up to 10 cm in diameter, with small granules and coarse sand filling the space between the pebbles. In contrast, in the sand bed, pebbles are buried in sand and the bed surface is composed of sand and fine granules. The exposed bedrock bed has a steep slope angle (10° to 40°), and no sediments exist. These four types occur throughout the stream length. In September 1989, new sandy materials, which were most likely to have originated from the unpaved road, were deposited in several locations on the bed surface,

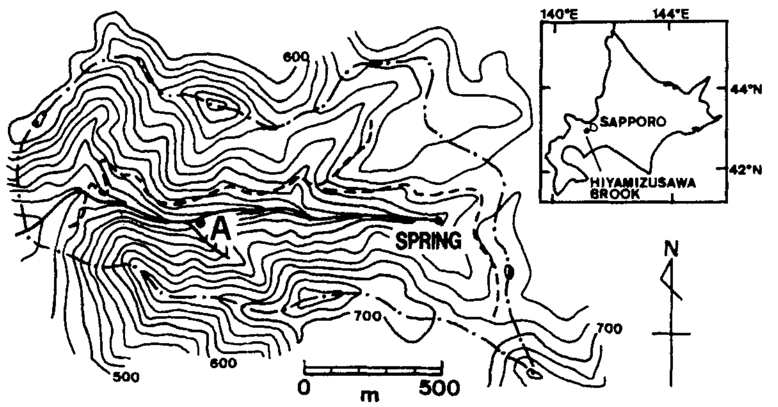

Figure 1. Topographic map of the study basin. The contour interval is 20 m. The dot–dash line indicates the drainage divide, and the dashed line shows an unpaved road

and in October 1989 this new sandy bed sediment comprised about 10 per cent of the bed surface upstream of Site A (see Figure 1) (Kurashige, 1993b). A more detailed description of this basin is provided by Kurashige (1993a).

River discharge and SSC on 7 and 8 April 1990 were examined at Site A (see Figure 1; Kurashige, 1993b). The river discharge was calculated from the stage–discharge curve obtained at this site. One litre of river water was sampled manually, and was vacuum filtered through preweighed cellulose nitrate filter paper (0·45 μm opening) to calculate the SSC. Figure 2 shows the time variation of river discharge and SSC on these days. The peak of SSC (109 mg l^{-1}) appeared at 11:00, whereas the peak discharge (0·097 m^3 s^{-1}) occurred at 13:00. The SSF at 11:00 and 12:00 was 8·42 g s^{-1} and 8·53 g s^{-1}, respectively, and it decreased to 5·08 g s^{-1} at 13:00, indicating that the amount of suspended-sediment supply at the peak discharge was less than that at the rising stage of discharge. This fact suggests that the storage of suspended-sediment source was exhausted, or suspended-sediment supply was controlled mechanically at the peak discharge.

Grain-size distributions of suspended sediment, regolith, road-bank sediment, river-bank sediment and river-bed sediment were also examined by Kurashige (1993b). Each grain-size distribution was plotted on probability paper, and was separated into several lognormal subpopulations by the method of Inokuchi and Mezaki (1974), which is similar to the separation method of Cassie (1954) usually used by ecologists (Figure 3). The cumulative frequency percentage at an inflection point q_p was detected first on the original distribution. The cumulative percentages of the coarse and the fine subpopulations were then expressed by

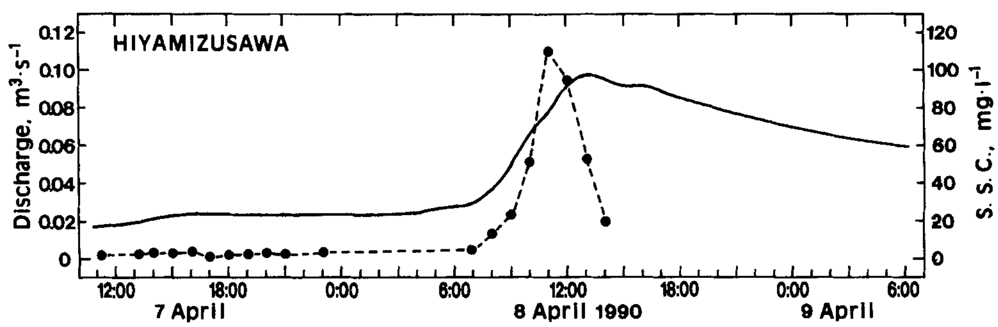

Figure 2. River discharge (solid line) and suspended-sediment concentration (solid circles) on 7 and 8 April 1990 (after Kurashige, 1993b)

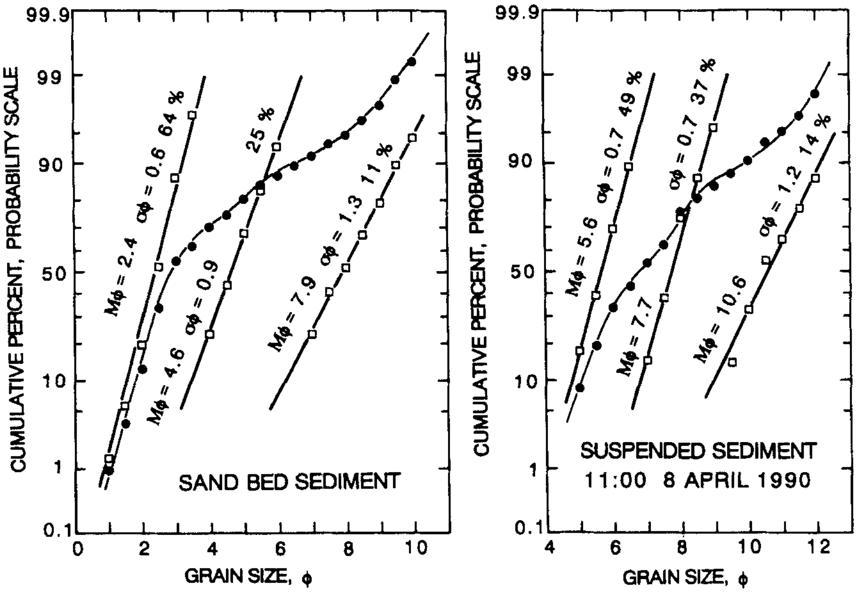

Figure 3. Grain-size distribution (solid circles) and lognormal subpopulations (open squares and bold solid line) plotted on probability paper. Fine solid line shows a distribution recombined from the subpopulations. Mean size ($M\phi$), standard deviation ($\sigma\phi$) and percentage of each subpopulation are also indicated. Left: sand bed sediment; Right: suspended sediment at 11:00 on 8 April 1990

$100q_o/q_p$ and $100(q_o - q_p)/(100 - q_p)$, respectively, where q_o is the cumulative percentage of the original distribution. The separation was continued until every subpopulation became lognormal. Further, the mean size ($M\phi$) and standard deviation ($\sigma\phi$) of each subpopulation was calculated by Inman's method. All subpopulations were again recombined to check that the recombined distribution became within the error range of the original one.

Table I shows the typical subpopulations of the sampled sediments. The percentage of population VI in the suspended sediment was low compared with those of populations IV and V. The distribution of population V in the suspended sediment was similar to that in the sand bed sediment. The $M\phi$ of population IV in the suspended sediment was finer than that of population IV in the sand bed sediment; but the standard deviation of population IV in the suspended sediment was smaller than that in the sand bed sediment. From these facts, Kurashige (1993b) concluded that the suspended sediment was supplied mainly from the sand bed sediment.

Kurashige (1993b) also sampled the suspended sediment in the summer rainy season, and compared its grain-size distribution with those of other sediments. He judged that most of the suspended sediment was supplied from hillslope in this season. This suggests that the fine grains in the sand bed sediment are exhausted in the summer rainy season, whereas they accumulate in the bed during winter. On the other hand, the fine grains in hillslope sediment are rarely supplied in the snowmelt season while the ground is covered with snow, but they are mainly supplied to the brook during the summer rainy season.

OUTLINE OF THE GRAIN LIFT MODEL

The grain lift model which was proposed by Kurashige (1985b) explained both the grain size of the suspended sediment and the time variation of SSC observed in Bankei Brook during the early snowmelt season.

The grain lift model is illustrated schematically in Figure 4A. In the first stage, the bed surface is covered with gravels, and fine grains are buried under these gravels (first stage in Figure 4A). When the tractive force τ on the river bed increases, some gravels start to move selectively depending on the magnitude of τ. Consequently, gaps are produced between the gravels. The fine grains are stirred up through these gaps

Table I. Mean sizes, standard deviations and percentages of subpopulations for sediment samples in the Hiyamizusawa Brook basin

	I		II		III		IV		V		VI	
	$M\phi$	$\sigma\phi$	$M\phi$	$\sigma\phi$	$M\phi$	$\sigma\phi$	$M\phi$	$\sigma\phi$	$M\phi$	$\sigma\phi$	$M\phi$	$\sigma\phi$
Regolith	−4·3 (11·7%)	1·1	−0·9 (14·3%)	1·2	2·4 (24·4%)	1·0	6·7 (35·7%)	1·3			9·9 (13·9%)	1·2
Road-bank sediment					0·4 (66%)	2·0	4·6 (21%)	0·9	6·8 (9%)	0·7		
River-bank sediment	−3·3 (10·1%)	0·8	0·0 (65·5%)	1·2	2·8 (16·4%)	0·7			6·8 (8%)	0·9		
Pebble bed sediment	−5·5 (81·0%)	1·2	−0·9 (17·7%)	1·4	2·5 (0·92%)	0·9	6·7 (0·38%)	1·6				
Sand bed sediment					2·4 (11%)	0·6	4·6 (64%)	0·9	7·9 (25%)	1·3		
Suspended sediment*							5·6 (49%)	0·7	7·7 (37%)	0·7	10·6 (14%)	1·2

* Sampled at 11:00, 8 April 1990

(second stage in Figure 4A). This stirring-up process continues as long as the fine grains remain in these gaps. The stirring-up process thus ceases when all the fine grains are extracted (third stage in Figure 4A). If a greater τ acts on the river bed, another progression from the second to the third stage begins. A further stirring-up process then occurs through the previously produced gaps. Fine grains are thus stirred up only from the upper layer of bed sediment.

In this model, the fine grains under the gravels are stirred up by the pressure difference (Δp) between the bottom and the top of the gravel layer on the bed surface. Einstein (1950) proposed the maximum diameter

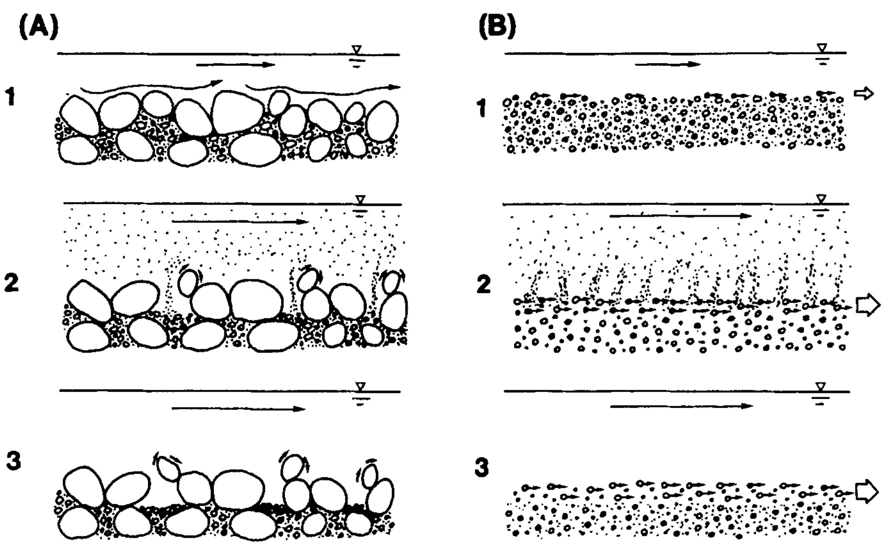

Figure 4. Schematic figure of the grain lift model. (A) Original grain lift model applied to stirring up from a gravel-bed river (modified from Kurashige, 1985b). (B) New grain lift model to explain stirring up from a sand bed river. The width of the open arrow head in (B) indicates the depth of the tractive layer on a sandy bed

(d_{max}) of grains stirred up by Δp as

$$\Delta p = \tfrac{2}{3}(\sigma - \rho) g\, d_{max} \tag{2}$$

where σ is the density of grains, ρ is the density of river water, and g is the acceleration due to gravity. Meanwhile, the relationship between τ and Δp, introduced theoretically by Christensen (1971), is written as

$$\frac{\Delta p}{\tau} = 0{\cdot}556\left\{\ln\left(\frac{10{\cdot}4\, D_{65}}{k_s} + 1\right)\right\}^2 \tag{3}$$

where k_s is the equivalent roughness height of the bed, and D_{65} is the diameter of the 65th percentile of the bed sediment distribution. From Equations (2) and (3), the maximum diameter of grains stirred up through the gaps can be calculated by

$$d_{max} = 0{\cdot}834 \frac{\tau}{(\sigma - \rho) g}\left\{\ln\left(\frac{10{\cdot}4\, D_{65}}{k_s} + 1\right)\right\}^2 \tag{4}$$

The maximum diameter of stirred-up grains was calculated from Equation (4) by substituting τ, k_s obtained in Bankei Brook. The calculated d_{max} was equivalent to the 0·1 per cent diameter of the sampled suspended sediment.

To simulate the time variation of suspended-sediment concentration, τ at a given time is first calculated by

$$\tau = \rho g R I \tag{5}$$

where R is the hydraulic radius, and I is the slope gradient of the river bed. Further, the maximum diameter of movable gravels under τ was calculated tentatively from Yalin's (1972, p. 80–87) diagram, and the area of the gaps produced was calculated from the grain-size distribution of the bed sediment. Next, the volume of fine particles under movable gravels was also calculated from the grain-size distribution. Alternatively, d_{max} could be calculated from Equation (4). The weight of fine grains stirred up from the gaps is thus computed for specific times, assuming that all grains smaller than d_{max} are completely suspended in the river water at each stage and the supply is exhausted in the next stage. The SSC at each time is thus obtained by $C = w/Q$, where C is the SSC and w is the weight of fine grains. Thus the temporal trend of SSC was calculated.

Nevertheless, in his calculation, Kurashige (1985b) standardized the SSC that becomes 1·0 at the peak concentration, and the actual value of SSC was not simulated, because the actual selective movement of mixed gravel bed remained unclear at that time. To calculate the value of SSC, the selective movement of mixed gravel bed must be combined, using, for instance, Komar's (1987) formula.

GRAIN LIFT MODEL FOR SAND RIVER BED

In Hiyamizusawa Brook, about 10 per cent of the river bed was covered with sand materials, and almost all of the suspended sediment was stirred up from the sand bed in the early snowmelt season (Kurashige, 1993b). The original grain lift model, however, only explains stirring up from a gravel bed. The process of stirring up from a sand bed must be considered to explain the time variation of SSC in this brook.

Figure 4B shows the new grain lift model applied to a sand bed. In the first stage, the bed surface is covered with sand, and only sand grains on the bed surface are moved by the tractive force τ acting on the surface. The stirring up of fine grains does not occur at this stage (first stage in Figure 4B). When τ increases, the surface layer moves downstream as the traction layer thickens. Fine grains buried in the tractive layer are consequently stirred up into the river water through gaps between sand grains. These gaps are probably produced between sand grains while they are moving (second stage in Figure 4B). This stirring-up process continues while fine grains remain available in the tractive layer. After all the fine grains are removed, no more stirring up occurs from the tractive layer (third stage in Figure 4B). If a greater τ acts on the bed surface, the tractive layer thickens downward, and another progression from the second to the third stage occurs. Since the coarser grains, which were not able to be stirred up in the previous sequence, have remained

in the previous tractive layer, the stirring up of the remaining grains also occurs from the previous tractive layer in this new sequence.

Assuming that all the sandy grains in the tractive layer are moving at the velocity U_b, the thickness of the tractive layer δ can be expressed as

$$\delta = \frac{q_b}{(1-\varepsilon)\sigma U_b} \tag{6}$$

where q_b is the bedload mass flux for a unit width, and ε is the porosity of sandy bed sediment.

Sato *et al.* (1956) obtained q_b as

$$q_b = \frac{\Phi(n)\rho}{(\sigma-\rho)} u*^3 F\left(\frac{\tau}{\tau_c}\right) \tag{7}$$

where $u*$ is the shear velocity, n is the roughness coefficient of Manning's equation, τ_c is the critical shear stress, and $\Phi(n)$ and $F(\tau/\tau_c)$ are functions of n and τ, respectively. They assumed that $\Phi(n)$ and $F(\tau/\tau_c)$ are constant at 0·62 and 1·0, respectively, while $n \geq 0{\cdot}025$. These values are comparable to conditions on the sand bed in Hiyamizusawa Brook ($n = 0{\cdot}04$).

Bagnold (1966) carried out an experiment on bedload transport, and obtained

$$U_b \approx 0{\cdot}13\, V \tag{8}$$

where V is the mean velocity of river flow.

Introducing Equations (7) and (8) into Equation (6), we get

$$\delta = 4{\cdot}77 \frac{\rho u*^3}{\sigma(\sigma-\rho)(1-\varepsilon)V} \tag{9}$$

On the other hand, the mean velocity V can be expressed by Manning's formula

$$V = \frac{1}{n} R^{\frac{2}{3}} I^{\frac{1}{2}} \tag{10}$$

and $u*$ is defined as

$$u* = \sqrt{\frac{\tau}{\rho}} \tag{11}$$

Introducing Equations (5), (10) and (11) into Equation (9) yields

$$\delta = \frac{4{\cdot}77\, n\rho I g^{\frac{3}{2}} R^{\frac{5}{6}}}{\sigma(\sigma-\rho)(1-\varepsilon)} \tag{12}$$

indicating that the δ increases with R.

Since the grain-size distribution of sand bed sediments and the hydraulic data of this brook are already known, the amount of suspended sediment supplied from sand bed sediment can thus be estimated from Equation (12), under the assumption that all grains finer than a critical value are stirred up from the tractive layer at a given time.

The sand bed surface was determined to have been flat from 10:00 to 14:00 on 8 April 1993, by plotting the stream power (τV) at each time and the grain size of sand bed sediment on Simons and Richardson's (1966) diagram. Moreover, the water-surface slope of the brook is likely to be equivalent to the river-bed slope, because the brook is a small mountain stream. Manning's n was therefore assumed to be almost constant, at least while the bed is flat.

To evaluate d_{max} from the sand bed, we must ascertain first whether Equation (4) yields the maximum grain size of suspended sediment obtained in the field study. The 0·1 per cent diameter of suspended sediment was 125 μm at 12:00 on 8 April 1990. Substituting this value for d_{max} in Equation (4), we get $k_s = 0{\cdot}03$ cm. On

the other hand, Simons and Richardson (1966) indicated that the d_{15} of sand bed sediment is equivalent to k_s of the flat sand bed. From the grain-size distribution of the sand bed sediment (see Figure 3), k_s was estimated to be 0·025 cm. This value is equivalent to the previously stated value of k_s, indicating that Equation (4) is fairly good for the estimation of d_{max} in this case. Since the sand bed surface was flat from 10:00 to 14:00, k_s remains constant, and accordingly Equation (4) was judged to be suitable for the estimation of d_{max} at least in this period.

CALCULATION OF SSC AND SSF

In this study, the SSC and SSF on 8 April 1990 was simulated by the new grain lift model. Here, as a first approximation, the average shear stress acting on the river bed between Site A and the headwater spring (see Figure 1) was assumed to stir up fine grains in this section. Thus the brook was not divided into several subsections in the calculation.

Ishii (1987) measured the discharge distribution between Site A and the spring at four times between 1984 and 1985. The river discharge is usually proportional to the distance from the spring, and its coefficient is proportional to the discharge at Site A. The average discharge at the section $\bar{Q}$ was thus calculated by interpolating these regression equations.

To calculate the average shear stress $\bar{\tau}$ acting on the bed surface, the average depth $\bar{h}$ is solved from Manning's equation by a bisection method, assuming that the section is rectangular. The average hydraulic radius $\bar{R}$ is further calculated, and $\bar{\tau}$ is given by $\bar{\tau} = \rho g \bar{R} \bar{I}$, where $\bar{I}$ is the average slope on the sand bed.

Here, we consider the mass of suspended sediment supplied from a sand bed of unit width with length L and with height δ in a unit time. Since the tractive layer has the velocity U_b, the sand grains move a distance equivalent to U_b in a unit time. Thus $L = U_b$.

The $\bar{Q}_i$ and further $\bar{R}_i$ at the time T_i are estimated from the discharge at Site A. Substituting $\bar{R}_i$ into Equations (8), (10) and (12), we can obtain U_{bi} and δ_i. Since fine grains are stored in pores between sand grains in the sand bed materials which have the volume $L_i\,\delta_i$, this volume is rewritten as v_i. The bulk volume of fine grains in v_i can be approximated to be $v_i\varepsilon$. Assuming that the porosity of fine grains is equivalent to that of sand grains, the potential mass of fine grains W_i, i.e. the maximum mass of fine grains possible to be stored in v_i, can be written as

$$W_i = v_i\varepsilon(1-\varepsilon)\sigma \tag{13}$$

On the other hand, $d_{max\,i}$ is calculated by Equation (4), and the cumulative weight per cent of fine grains with the diameter $d_{max\,i}$ is here written as P_i. The mass of fine grains S_i stirred up from v_i during the time between T_{i-1} and T_i is then given by

$$S_i = \frac{\delta_i - \delta_{i-1}}{\delta_i}\frac{100 - P_i}{100} W_i + \left(1 - \frac{\delta_{i-1}}{\delta_i}\frac{100 - P_{i-1}}{100} - \frac{\delta_i - \delta_{i-1}}{\delta_i}\right)\frac{P_i - P_{i-1}}{P_i} W_i \tag{14}$$

The first term of Equation (14) indicates the mass of grains stirred up from the layer between δ_{i-1} and δ_i. The second term indicates that mass from the layer shallower than δ_{i-1}.

The total amount of fine grains stirred up from the sand bed S_{Ti} can be expressed as

$$S_{Ti} = \frac{S_i X}{L_i} \tag{15}$$

where X is the total distance over which sandy bed is deposited.

In addition, fine grains are also stirred up both from the cobble bed and the pebble bed. The amount of fine grains stirred up from the cobble and pebble bed is calculated by the method of Kurashige (1985b), and this amount is here given as G_i.

The SSC C_i at the time T_i is thus written as

$$C_i = \frac{S_{Ti} + G_i}{q_i(T_i - T_{i-1})} \tag{16}$$

where q_i is the river discharge for a unit width of the brook at the time T_i. Accordingly, the SSF F_i is given by

$$F_i = C_i\bar{Q}_i \tag{17}$$

The result of the calculation is shown in Figure 5. The time step is one hour, and the stirring up of grains is assumed to be completed within each time step. Since the water takes no more than 20 min to flow from the spring to Site A, the time lag from the sediment source to Site A was not considered. Here in the calculation, w and I on the sand bed were set as 1 m and sin 1°, respectively. Ten per cent, 30 per cent and 50 per cent of the river bed was set to be covered with sand bed, pebble bed and cobble bed, respectively, as Kurashige (1994b) reported in this basin. The previous maximum discharge in the snowmelt season was $0{\cdot}060\,\mathrm{m^3\,s^{-1}}$, thus it is assumed that all the grains that it was possible to stir up under this condition were already exhausted. The calculated trend of the temporal change of SSC and SSF is similar to the field data (see Figure 5). In the calculation, the percentage of suspended sediment supplied from the cobble-and-pebble bed ranged between 8 and 12 per cent, and the other 88 to 92 per cent was supplied from the sand bed.

The calculated d_{max} ranged between $3{\cdot}5\phi$ and $3{\cdot}9\phi$ from time 10:00 to 13:00, whereas the 1 per cent diameters of suspended sediment were $3{\cdot}9\phi$ to $4{\cdot}1\phi$ (see Figure 3), indicating that the grain lift model also provides a good estimate for the grain size of suspended sediment.

DISCUSSION AND CONCLUSION

The SSC or SSF stirred up from sand bed was classically estimated from log concentration profile which was calculated theoretically from log velocity profile of river water (e.g. Lane and Kalinske, 1941; Einstein, 1950). In these studies, SSC near the bed surface is needed to obtain the concentration profile. The stirring-up process was not considered. Moreover, the SSC of grains smaller than silt size has uniform profile (Straub, 1932), indicating that the calculation based on the log profile itself is inadequate for the SSC of fines.

In this study, the stirring up of fines was assumed to be generated by the average shear stress acting on the bed of the river section under discussion, and the section was not divided into several subsections. However, in an actual suspension event, the shear stress varies with the distance from the headwater spring, and the amount of stirred-up grains also varies accordingly with the distance. Moreover, on the sand bed site near the headwater spring, sand from the river bed is transported downstream. Thus the layer from which fine grains are stirred up may deepen readily. On the downstream site with a sand bed, however, the tractive layer is composed of both the sand grains transported from upstream and those which begin to move at this

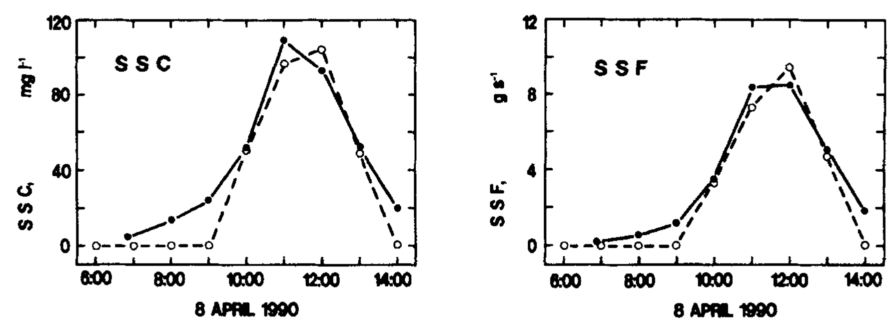

Figure 5. Simulated (open circles) and measured (solid circles) SSC (left side) and those of SSF (right side) at Site A

site. The stirring-up layer probably does not deepen readily at this site. The river bed must be subdivided into several subsections to consider these problems.

The values of calculated SSC and SSF are underestimated both on the rising stage and on the falling stage of the time variation (Figure 5). This underestimation is possibly caused by the simple nature of the model; it may be improved if the river section is divided into several subsections and the stirring up of fine grains is recalculated under such conditions. Nevertheless, the trends of SSC and SSF were estimated well in this calculation.

The grain lift model applied to the stirring up of fine grains from a sand bed sediment explained well the trend of SSC and SSF obtained in Hiyamizusawa Brook in the early snowmelt season. In this calculation, the grain size of suspended sediment was also estimated, and the calculated grain size was equivalent to the measured grain size.

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